Determination of metrological structural resolution of a CT system using the frequency response on surface structures

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Abstract

A novel method for the determination of the structural resolution of a computed tomography (CT) system is presented. The method uses the frequency response of the CT system while measuring the surface of an Aperiodic Spatial Frequency Standard (ASFS). The geometry of the standard allows it to investigate a broader range of possible structural resolutions using just one standard. Simulations and experiments, using CT with different acquisition parameters and a fringe projection system, show that the method is a promising alternative for determining the structural resolution of a measurement system.

Keywords

Dimensional metrology, computed tomography, structural resolution, frequency response

1 Introduction

While Computed Tomography (CT) has been in clinical use for decades, it is a rather new technology in the field of dimensional metrology. Especially its unique capability of enabling a contactless measurement of the whole part (including inner geometries) in one scan triggered the rapid propagation of dimensional CT measurements in scientific and industrial use.

Compared to other technologies used in dimensional metrology, the measurement process of CT is rather complex. Detailed explanations are given in the references cited (see [1], [2] and [3]). Basically, a CT system consists of four main components: an X-ray tube, a rotational stage, an X-ray detector and a computer system for data evaluation. To perform a measurement, the object to be measured is placed on the rotational stage. The X-rays propagate through the object and are attenuated in dependency of the material, the density of the object and the path length travelled in the object. In the first step, a large number (approximately 800 to 2 000) of these 2-D projections from different angular positions are detected. As a result, the attenuation along the paths of the X-rays is measured by the detector's pixels. In the next step, the 3-D volume is reconstructed from the 2-D projections. In the course of this, the local X-ray attenuation coefficient of the object, split into small voxels (**vo**lume pi**xel**s), is determined. Up to this point, the procedures are basically identical for medical and metrological CT. However, to perform dimensional measurements, two additional steps are necessary. Using the voxels' information about the local attenuation coefficient, the position of the object's surface is determined. In the last step, geometric elements are associated with the surface data and the dimensional measurements are carried out.

An important characteristic determining the quality of a CT measurement is the resolution. According to [4] and [5], for coordinate measuring technology in the field of CT it has to be distinguished between positional resolution and structural resolution. This article focuses on the latter, which describes 'the size of the smallest structure that can still be measured dimensionally' [5]. Due to the complexity of a CT measurement, a large number of quantities influence the structural resolution. Firstly, the finite size of the detector pixels limits the resolution of the 2-D projection and, consequently, the resolution of the 3-D volume and all following evaluation steps. While it is, to a certain extent, possible to compensate for this by increasing the geometric magnification, the finite size of the X-ray spot and scatter effects inside the detector [6] cause unsharpness within the projection data. Smoothing filters, which are applied to the projection, volume and/or surface data to decrease the impact of noise, also decrease the resolution. Then again, noise in the measurement can render it impossible to distinguish between small features and noise. The schematic effect of a CT measurement with limited structural resolution is depicted in Figure 1. While larger structures are still visible, smaller structures are no longer perceived as separated and, therefore, it is no longer possible to measure them dimensionally. This behaviour resembles the mechanical filtering effect when measuring a surface with a stylus with a finite tip radius [7].

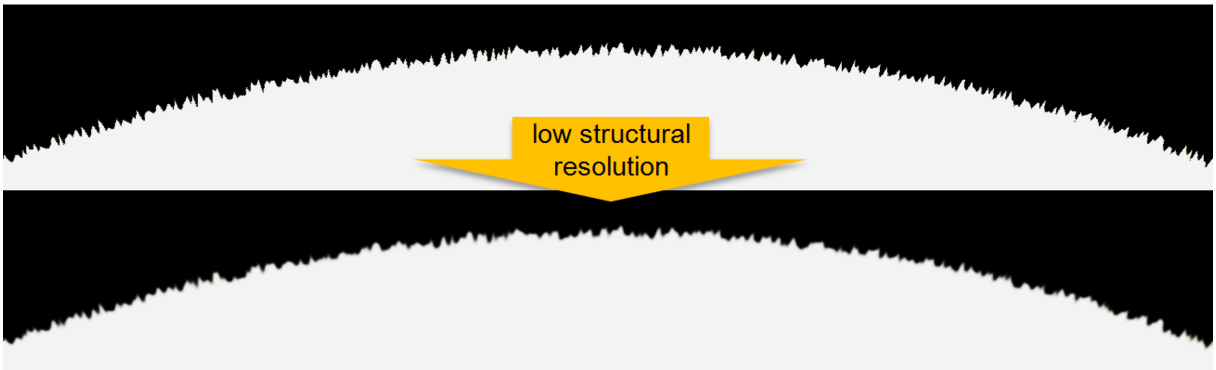

Figure 1: Schematic illustration of the blurring effect of a CT measurement with limited structural resolution on volume data.

As the structural resolution of a CT system varies for different acquisition parameters and data evaluation methods, the structural resolution has to be defined for specific conditions. For medical CT, the modulation transfer function (MTF) is used to characterize the resolution of the volume data. It is explained more in detail in [1] and [8]. The MTF is a very powerful method to characterize the resolution of the volume data, but it does not include the step of surface determination, which is crucial for dimensional measurements.

To determine the structural resolution for dimensional measurements, [5] suggests measuring small calibrated spheres. The sphere’s diameter is equal to the structural resolution, if the CT system is capable of measuring it correctly. However, especially for small structural resolutions and varying acquisition parameters, a large number of calibrated microspheres would be needed to cover the whole range of possible structural resolutions.

Several investigations have been carried out to examine alternative methods to determine the structural resolution for CT measurement. Weiß et al. determined the 3-D resolution using periodic 3-D structures [9]. Carmignato et al. investigated the ‘Hourglass’ standard. This approach uses the phenomenon, that the surface data extracted from a measurement of two touching spheres is distorted in proximity of the contact point [10]. Bartscher et al. examined how measurements of sharp edges result in rounded off edges in the surface data [11]. In a further development, Illemann et al. developed a reference standard with edges of small radii. By evaluating the measured and the calibrated radius of the standard, an analogue Gaussian broadening of the whole measurement system can be determined [12]. Arenhart et al. investigated the surface content surface function by examining a multi-wave standard and the transmission of sinusoidal spatial frequencies [13] [14].

2 Approach to determine structural resolution of dimensional CT measurements

2.1 Aperiodic Spatial Frequency Standard

To determine the structural resolution of a dimensional CT measurement, an Aperiodic Spatial Frequency Standard (ASFS) was developed. In the first version, the ASFS is a cylindrical object with small aperiodic structures on the side of the cylinder as depicted in Figure 2. As the structures deviate from sinusoidal shapes and, as they are positioned aperiodically along the side of the cylinder, the ASFS features spatial frequencies from a wider range when performing a Fourier analysis of the surface data.

To determine the structural resolution, the ASFS is scanned by a CT system with defined acquisition parameters. Using a defined surface determination method, data points along circumferential lines as in the roundness measurement are extracted. A Fourier analysis is carried out on the surface data to yield the amplitudes of different spatial frequencies. By comparing these amplitudes to the result of a reference measurement, the frequency response (the transmission, or alternatively, damping) of the CT system for different spatial frequencies can be evaluated, which makes it possible to derive information about the structural resolution of the CT system. As the method works on extracted surface data, the whole measurement process is taken into consideration.

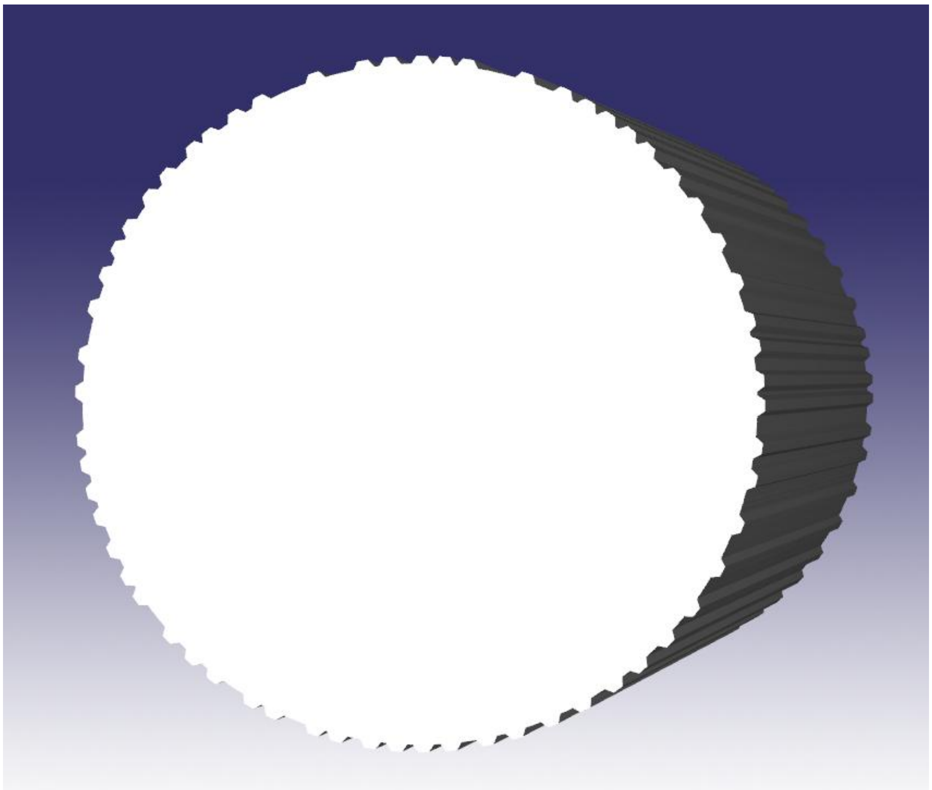

Figure 2: Schematic model of a cylindrical ASFS

This method tries to combine the advantages of the approaches of Arenhart et al. and Illemann et al. By measuring a large number of similar structures simultaneously and calculating the transmitted amplitudes of different spatial frequencies, stable results and straightforward evaluation are achieved. By measuring structures deviating from sinusoidal shape, a large range of possible structural resolutions can be covered by a single standard. To a certain extent, a transfer of the calculation of the MTF from volume data (grey values) to surface data (coordinates) is realised.

2.2 Simulations

For simulative investigations, a cylindrical ASFS with aperiodically distributed, from sinusoidal shapes deviating geometries was modelled (see Figure 3). The width of the geometries is approximately 50 µm. The simulations have been carried out with the software ‘aRTist’ (**a**nalytical **R**adiographic **T**esting **i**nspection **s**imulation **t**ool) by BAM (Federal Institute for Materials Research and Testing) [15]. The CT system of the Institute of Manufacturing Metrology, a Werth TomoCheck 200 3D, is modelled realistically in aRTist, with all important error sources taken into account. Measurements of varying acquisition parameters were reproduced to investigate the transmission of different spatial frequencies of the ASFS by the CT system.

Figure 3: Cross section of ASFS used for simulative investigations

A strong correlation with the geometrical magnification is visible. With increasing voxel size, the damping of higher frequencies increases (see Figure 4). Using the spatial frequency spectrum of the CAD data as reference, the transmission of amplitudes for different spatial frequencies can be calculated (see Figure 5). For a voxel size of 10 µm, about 50 % of the amplitude is transmitted at the spatial frequency of 8 mm^{-1}. For higher spatial frequencies, the transmission decreases. As the amplitude at 12 mm^{-1} is almost zero, the calculation of the transmission for these spatial frequencies is rather unstable.

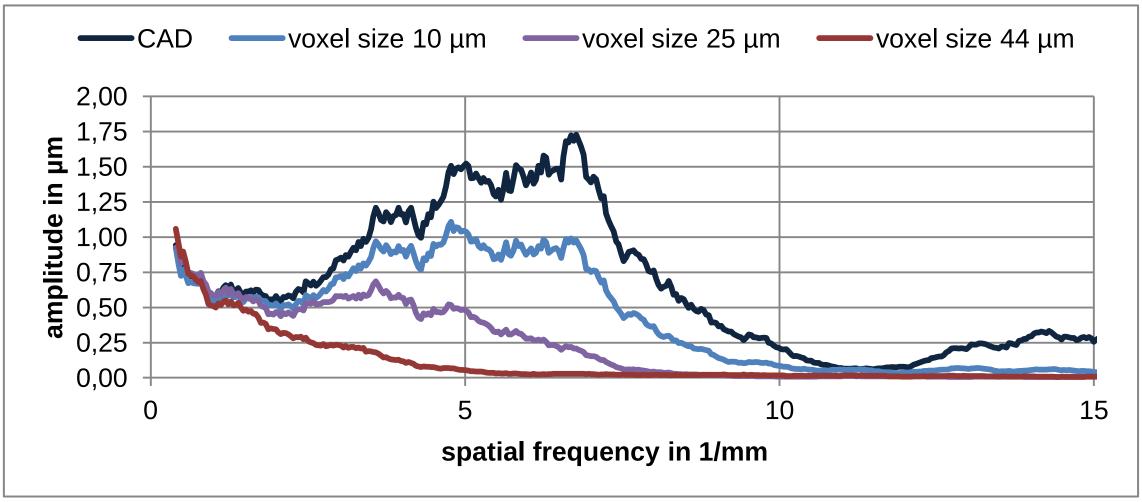

Figure 4: Simulated amplitudes for different geometrical magnifications.

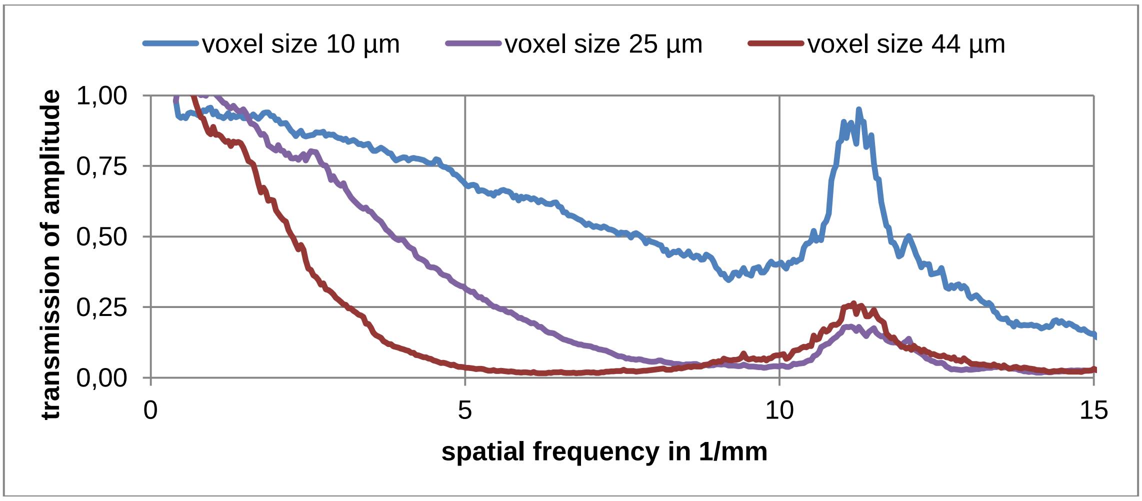

Figure 5: Simulated transmission of spatial frequencies for different geometrical magnifications.

Likewise, the size of the X-ray spot has a significant influence on the transmission of different spatial frequencies (see Figure 6). When comparing cross sections of the simulated data sets (Figure 7), it is evident that a large spot size leads to blurred projections and volume data. As a result, small structures are no longer recognizable in the extracted surface data.

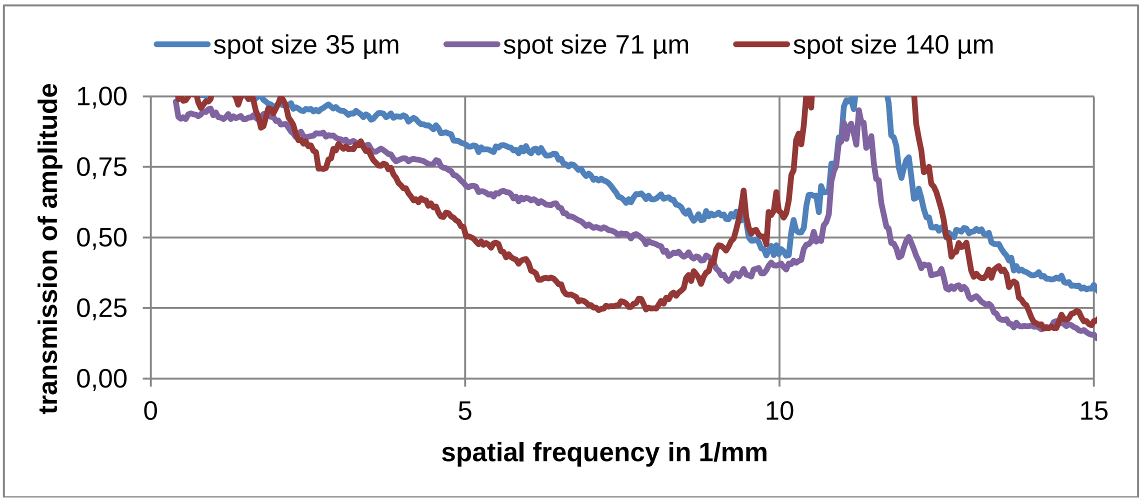

Figure 6: Simulated transmission of spatial frequencies for different X-ray spot sizes

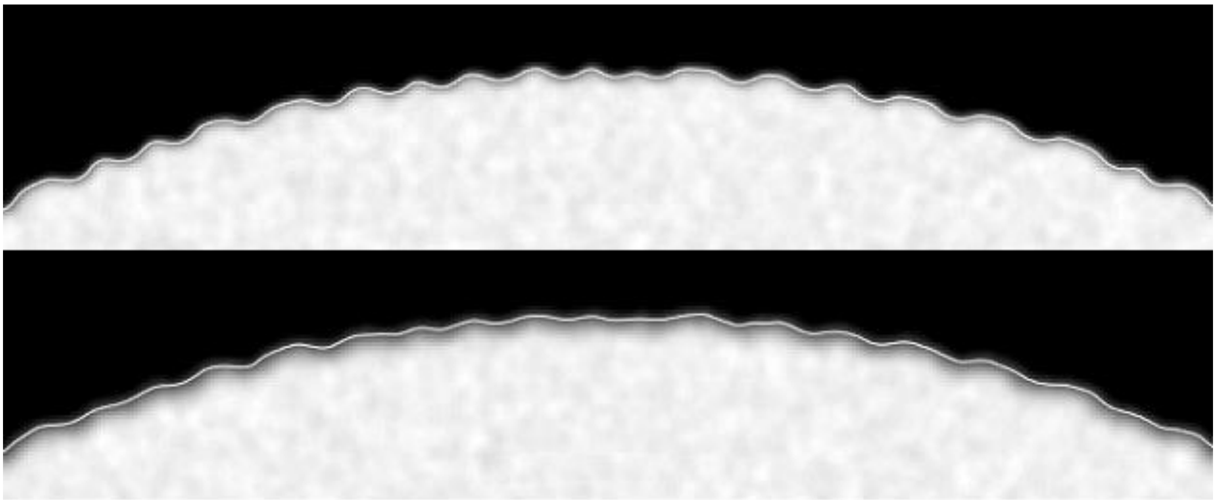

Figure 7: Comparison of simulated cross sections for spot sizes of 35 µm (top) and 140 µm (bottom). The white line indicates the extracted surface.

The unsharpness of the detector itself has a similar impact on the transmission characteristics (Figure 8). While small structures are still identifiable for an ideal detector, they vanish when the realistic properties of the detector are considered.

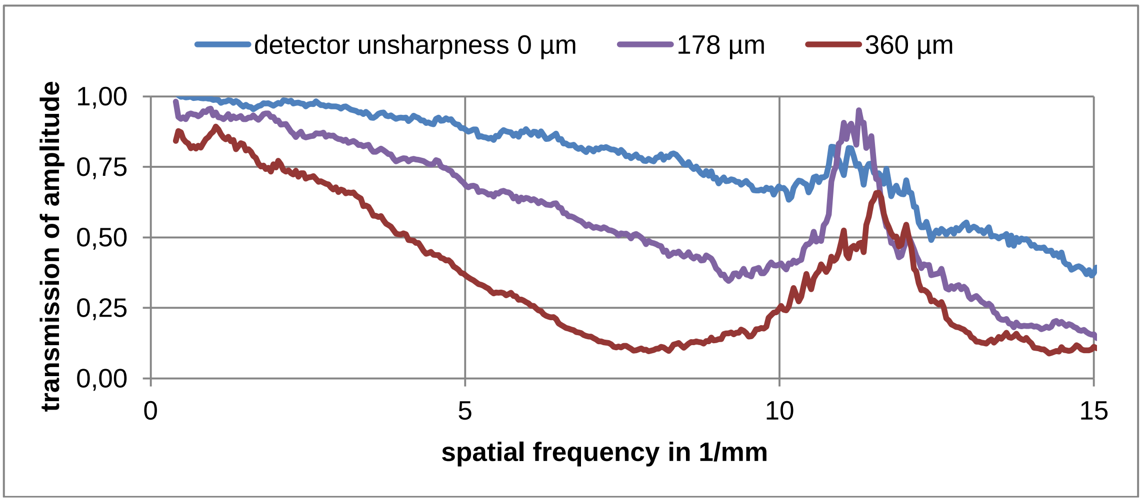

Figure 8: Simulated transmission of spatial frequencies for different settings of the detector unsharpness.

The number of averaged projections per angular position influences the noise in the measurement results. As expected, it has no influence on the general characteristic of the transmission curve. However, for smaller structures, noise leads to unstable results (see Figure 9).

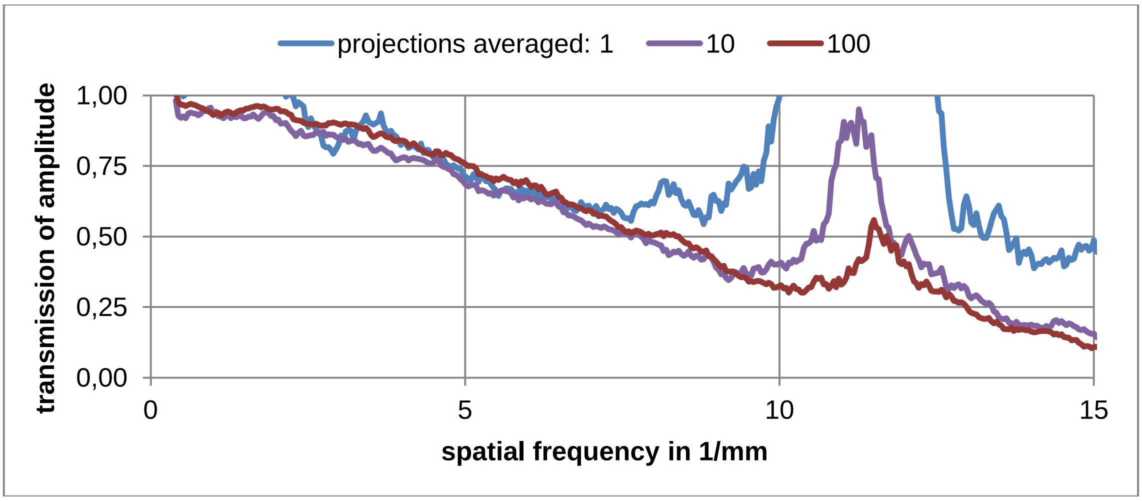

Figure 9: Simulated transmission of spatial frequencies for different settings of averaged projections.

2.3 Experiments

A first test sample made of acrylic glass was manufactured using a laser cutter (see Figure 10). As filigree geometries are not achievable, the geometric structures have a size of several millimetres. However, with costs of about 0.10 € per piece, the production at FAU FabLab is extremely economic.

Figure 10: Cross section of a cylindrical ASFS used for experimental investigations.

Comparing a CT measurement of 30 µm voxel size with a measurement at 88 µm voxel size with additional Gaussian filtering of the volume data over 15 voxels, it is clearly visible that the damping increases for large spatial frequencies (see Figure 11). In comparison with a measurement of a fringe projection system (ATOS Compact Scan 2M), it is noticeable that higher harmonics are not detected correctly by the fringe projection system as noise superimposes the signal (see Figure 12).

For all measurements, it is obvious that the sample lacks the filigree structures that are needed to generate significant amplitudes for higher spatial frequencies. It is possible to draw some conclusions by plotting the amplitudes on a logarithmic scale, but the significance of these first investigations is limited due to the low signal for large spatial frequencies.

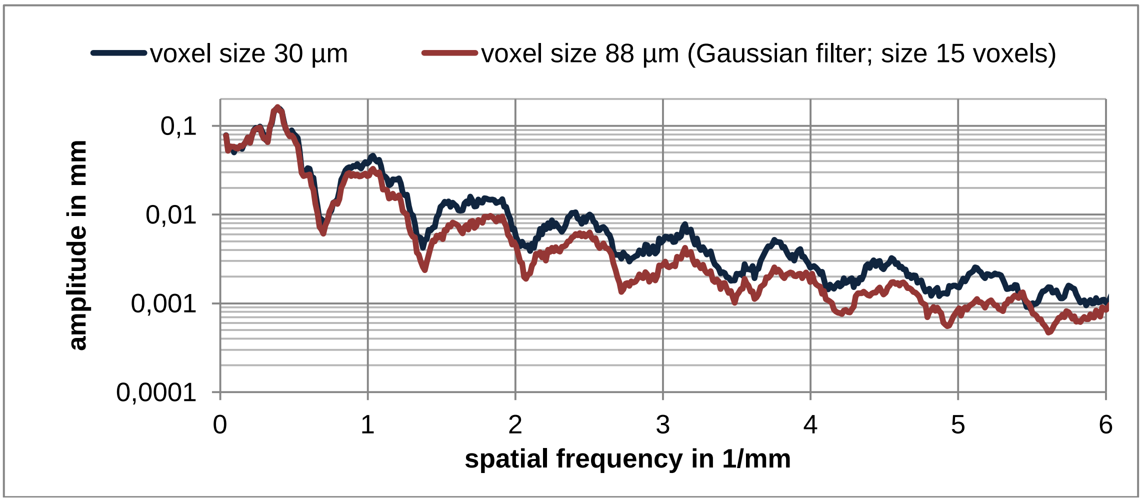

Figure 11: Measured amplitudes for different acquisition parameters.

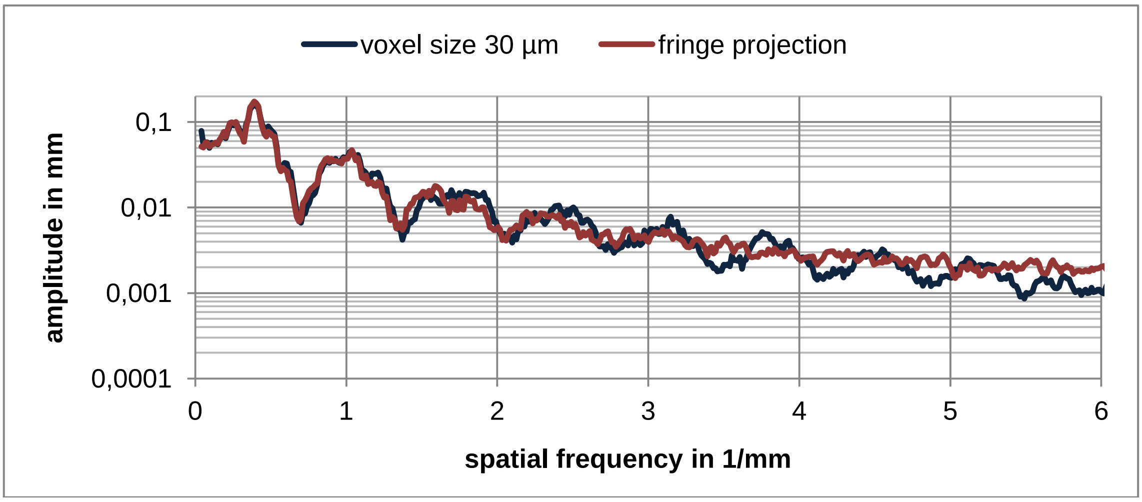

Figure 12: Measured amplitudes in comparison with a fringe projection system.

3 Conclusion and outlook

It has been shown that the presented method is a promising alternative for determining the structural resolution. The characteristic curves of the transmission resemble the MTF that is used to determine the spatial resolution of a CT system. From this perspective, the concept of the MTF was transferred from volume data to surface data. Analogously, it is one possibility to define the structural resolution by determining the largest structure whose amplitude is transmitted by a certain percentage (e.g. 50 %).

Simulations have shown that the design of the ASFS allows determining the transmission of the amplitudes for a broader range of spatial frequencies using just one sample. The results are as theoretically expected: the geometric magnification, the focal spot size and the detector unsharpness are strongly influencing the general characteristic of the curve. The number of averaged frames per angular position does not change the characteristic, but leads to noise, which is significant especially for large spatial frequencies (i.e. small structures). Experimental investigations using a first prototype support these results and indicate that it is possible to compare the structural resolution of different sensors.

However, a standard with much smaller geometrical features has to be manufactured for futher investigations. At the same time, the geometries of the small aperiodic structures will be adjusted to achieve a more uniformly distributed spatial frequency spectrum. As cylindrical geometries are difficult to measure for some CMMs like surface profilers, a linear ASFS will be developed.

The results of these investigations will be used in the EMRP project ‘microparts’. In this project, a virtual metrological CT (VMCT) is being developed to enable numerical uncertainty determination for dimensional CT measurement. To ensure a realistic modelling of the CT system’s characteristics for the measurements of small geometries, this method will be used to validate the consistency of simulated with experimental results.

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